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### **► To cite this version:**

Caroline Bogliotti, Willy Serniclaes, Souhila Messaoud-Galusi, Liliane Sprenger-Charolles. Discrimination of speech sounds by children with dyslexia: Comparisons with chronological age and reading level controls. *Journal of Experimental Child Psychology*, 2008, 101, pp.137-155. 10.1016/j.jecp.2008.03.006 . halshs-00468930

**HAL Id: halshs-00468930**

**<https://shs.hal.science/halshs-00468930>**

Submitted on 1 Apr 2010

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Discrimination of speech sounds by children with dyslexia:  
Comparisons with chronological age and reading level controls.

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Running title: Categorical Perception deficit and dyslexia

## ABSTRACT

Previous studies have shown that children suffering from developmental dyslexia have a deficit in categorical perception of speech sounds. The aim of the present study is to better understand the nature of this categorical perception deficit. In this study, categorical perception skills of children with dyslexia were compared to those of chronological age and reading level controls. Children identified and discriminated /do-to/ syllables along a Voice Onset Time (VOT) continuum. Results showed that children with dyslexia discriminated among phonemically contrastive pairs less accurately than did chronological age and reading level controls, and showed higher sensitivity in the discrimination of allophonic contrasts. These results suggest that children with dyslexia perceive speech with allophonic rather than phonemic units. The origin of allophonic perception in the course of perceptual development and its implication for reading acquisition are discussed.

*Keywords:* Dyslexia, Categorical Perception, Speech Development, Allophonic Perception.

## INTRODUCTION

Dyslexia is characterized by a severe reading impairment without other physiological or psychological problems (Stanovich, 1996; Shaywitz, 1998; Lyon, Shaywitz, & Shaywitz, 2003). There is a growing amount of evidence that phonological factors play an crucial role in the acquisition of normal reading and that phonological processes are impaired in children affected by dyslexia (Snowling, 2000; Ramus, 2003; Ramus, Pidgeon, & Frith, 2003a; Ramus, Rosen, Dakin, Day, Castellote, White, & Frith, 2003b; Sprenger-Charolles, Colé, & Serniclaes, 2006). Indeed, it is now well established that to learn to read in alphabetic orthographies, it is necessary to learn to map graphemes with phonemes, this process being easier when children can use a shallow orthography than when they are faced with an opaque orthography (for instance, in Spanish compared to English, see for a review, Sprenger-Charolles et al., 2006). However, whatever the opacity of the orthography, it has nonetheless been shown that early reliance on grapheme-phoneme correspondences is a bootstrapping mechanism for future reading acquisition. For instance, children who were the best early decoders of grapheme-phoneme correspondences turned out to be the best readers. Evidence of this is provided by longitudinal studies (Share, 1995; Sprenger-Charolles et al., 2006), and by the fact that training based on grapheme-phoneme correspondences is the most effective (Ehri, Nunes, Stahl, & Willows, 2001a; Ehri, Nunes, Willows, Schuster, Yaghoub-Zadeh, & Shanahan, 2001b). In addition, dyslexics experience great difficulties when they have to rely only on grapheme-phoneme correspondences to read, without the help of their lexical knowledge, i.e., for the reading of unknown words, or pseudo-words. Indeed, such a deficit is the key characteristic of

developmental dyslexia, for this deficit is consistently found in group studies, even as compared to reading level controls (Rack, Snowling, & Olson, 1992; Van Ijzendoorn & Bus, 1994; for French data, see Sprenger-Charolles, Colé, Lacert, & Serniclaes, 2000) and is systematically observed in most participants in single and multiple case studies (Sprenger-Charolles et al., 2006).

Finally, a good level in phonemic awareness seems indispensable for making appropriate use of grapho-phonemic correspondences. Indeed, among the pre-reading abilities linked to reading acquisition, phonemic awareness has been shown to be the best predictor of future reading level, while evidence for the unique contribution of syllabic awareness and rhyme awareness is very limited (for a review, Sprenger-Charolles et al., 2006). In addition, deficits in phonemic awareness have been found to be more reliable than deficits in phonological short-term memory or in rapid naming (e.g. in English: Bruck, 1992; Chiappe, Stringer, Siegel, & Stanovich, 2002; Pennington, Cardoso-Martins, Green, & Lefly, 2001; in German: Wimmer, 1993). However, some discrepancies between the results of dyslexics faced with a transparent orthography have been reported in regard to phonemic awareness. Indeed, such a deficit was observed in some studies (e.g. in Spanish: Jimenez-Gonzalez, & Ramirez-Santana, 2002; in Czech: Caravolas, Volin, & Hulme, 2005; in German: Landerl, Wimmer, & Frith, 1997; Wimmer, 1993; in French: Sprenger-Charolles, et al., 2000; Ziegler, Castel, Pech-Georgel, George, Alario, & Perry, in press) but not in other studies (e.g. Landerl & Wimmer, 2000). Nevertheless, it seems difficult to argue that the dyslexic's deficit in phonemic awareness is a mere consequence of reading acquisition since in some of these studies that deficit was observed relative to reading- (or

spelling) matched control peers (e.g. in English: Bruck, 1992; Chiappe et al., 2002; Pennington et al., 2001; in Spanish: Jimenez-Gonzalez, & Ramirez-Santana, 2002; in Czech: Caravolas et al., 2005), and even before reading acquisition in future dyslexics compared to future average readers (e.g. Sprenger-Charolles et al., 2000).

Most of the studies in this field have used tasks involving the explicit segmentation of spoken words (phonemic counting, phonemic deletion, and phonemic inversion). However, there is also some evidence for implicit phonological deficits in dyslexic children. Boada & Pennington (2006) showed that children affected by dyslexia performed consistently worse than controls when more segmental representations were required in lexical gating, priming and syllable similarity tasks. This might reflect either a specifically segmental deficit or a core deficit in phoneme representation, the latter having in turn several different consequences for achieving segmentation and other tasks. Interestingly, the results of speech discrimination experiments suggest that dyslexic children indeed have a deficit in phoneme representation and which would be characterized by the use of allophonic, rather than phonemic, representations of speech sounds (Serniclaes, Van Heghe, Mousty, Carré, & Sprenger-Charolles, 2004). Allophones correspond to mere contextual variants of phonemes in the language of interest, while being phonemic in other languages. For instance, some languages display a twofold distinction between /d/ (voiced), /t/ (voiceless) and /t<sup>h</sup>/ (voiceless aspirated) stops whereas other languages only have a single d/ t<sup>h</sup> distinction. However, in these languages the /t/ consonant is also present as an allophone of either the /d/ or / t<sup>h</sup>/ phoneme.

### Categorical Perception deficits in dyslexia

A fairly large number of studies on the perceptual discrimination of speech sounds have reported categorical perception deficits in people affected by developmental dyslexia (Brandt & Rosen, 1981; Godfrey, Syrdal-Lasky, Millay, & Knox, 1981; De Weirtdt, 1988; Reed, 1989; Serniclaes, Sprenger-Charolles, Carré, & Démonet, 2001). The data presented in this paper lend further support to the existence of a phonemic discrimination deficit in dyslexia and also to the claim that this deficit reflects a specific mode of speech perception based on allophonic rather than phonemic units. Before examining the arguments in support of the allophonic explanation of dyslexia, we first provide a unified view of the categorical perception deficits.

Three different kinds of speech categorization deficits have been evidenced in people affected by dyslexia, depending on the experimental paradigm under use: discrimination alone, labeling alone and discrimination vs. labeling. While each of these three deficits is somehow related to “categorical perception”, there are also important differences between them. Discrimination between stimuli which lie across a phoneme boundary is normally better than discrimination between stimuli located within a category (see Figure 1).

Further, the observed discrimination scores should normally coincide with those expected from labeling. The magnitude of the boundary discrimination peak (Wood, 1976) and the correspondence between the observed and expected discrimination scores (Liberman, Harris, Hoffman, & Griffith, 1957; 1978) are two different indexes of categorical perception and both have been used in the studies on dyslexia. In this paper, the categorical

perception deficit will refer to a reduction in discrimination peak, unless otherwise specified. Still another index of categorical perception is based on the slope of the labeling function, a shallower slope indicating a lesser degree of categorical “precision” (Simon & Fourcin, 1978). We will refer to the reduction in the slope of the labeling function as the "categorical labeling" deficit.

Various studies evidenced a Categorical Perception deficit by showing that the phoneme discrimination peak was smaller in dyslexics vs. chronological age controls (Brandt & Rosen, 1981; Godfrey et al., 1981; De Weirtdt, 1988; Reed, 1989; Serniclaes et al., 2001). Some studies also compared observed discrimination scores to those expected from labeling data and they showed that the discrepancy was larger for the children affected by dyslexia, which reveals another form of Categorical Perception deficit (Brandt & Rosen, 1981; Godfrey et al., 1981; Werker & Tees, 1987). Finally, the slope of the labeling function was also found to be shallower in dyslexics vs. chronological age controls, thus evidencing a categorical labeling deficit (Reed, 1989; Manis, McBride-Chang, Seidenberg, Keating, Doi, Munson, & Petersen, 1997; Joanisse, Manis, Keating, & Seidenberg, 2000; Chiappe, Chiappe, & Siegel, 2001; Maassen, Groenen, Crul, Assman-Hulsmans, & Gabreëls, 2001).

*Insert Figure 1 here*

Further, studies with adult developmental dyslexics did not find either a Categorical Perception or a labeling deficit in the behavioral responses although categorical differences were present in the neuronal recordings (Ruff, Cardebat, Marie, & Demonet, 2002; Ruff,



Marie, Celsis, Cardebat, & Demonet, 2003; Dufor, Serniclaes, Balduyck, Sprenger-Charolles, & Démonet, 2006).

Most of the previous studies dealing with the Categorical Perception deficit in dyslexia only used chronological age controls. The presence of a Categorical Perception deficit in dyslexics relative to chronological age controls is commonplace in the literature on dyslexia (Werker & Tees, 1987; Serniclaes et al., 2001; Serniclaes, Van Heghe, Mousty, Carré, & Sprenger-Charolles, 2004; Maassen et al., 2001). The few studies which used both chronological and reading level controls failed to find significant differences in Categorical Perception between dyslexics and reading level controls (in French: Boissel-Dombreval & Bouteilly, 2003; in Dutch: Foqué, 2004; in English: Manis & Keating, 2004). However, the deficit was present though not significant in one of these studies (Foqué, 2004), and a strong Categorical Perception deficit was found for those dyslexics who also had Specific Language Impairment in another study (Manis & Keating, 2004). This suggests that a Categorical Perception deficit might also be present when comparing dyslexic children to reading level controls. Comparisons with reading level controls allow to discard differences in reading level as a possible cause of the deficits associated to dyslexia (e.g. Bryant & Impey, 1986). One of the objectives of the present study is to provide a further test of the differences in Categorical Perception between dyslexics and reading level controls.

Origin of the categorical perception deficit: allophonic mode of speech perception

The Categorical Perception deficit in dyslexia is characterized not only by reduced discrimination of across-category differences between stimuli straddling the phonemic boundary but also by increased discrimination of within-category differences (Serniclaes et al., 2001). Furthermore, dyslexics exhibited a higher-sensitivity to phonetic distinctions between different members of the same phoneme category (Serniclaes et al., 2004).

The enhanced sensibility to phonetic components of phonological contrasts could originate from an allophonic mode of perception. Allophonic perception means that phonetic features which are not relevant for native language phonology remain discriminable, possibly as a consequence of deviant perceptual development in early childhood. Infants are born with the ability to distinguish all the phonetic contrasts in the world's languages (Eimas, Siqueland, Jusczyk, & Vigorito, 1971; Lasky, Syrdal-Lasky, & Klein, 1975; Streeter, 1976; Aslin, Pisoni, Hennessy, & Perey, 1981). This ability would be either enhanced or, instead, somehow neutralized depending on the relevance of the contrasts in the linguistic environment of the listener (Werker & Tees, 1984;1999). For example, infants younger than 6 months are able to discriminate 3 voicing categories separated by two VOT boundaries (Lasky et al., 1975; Streeter, 1976; see Figure 2a and Footnote 1). However, after about six months of age voicing perception differs according to native language. Infants raised in an English environment react more to the positive VOT boundary than to the negative VOT boundary (Aslin et al., 1981; see Figure 2b). However, the enhancement of a boundary is not the only possible developmental pathway; in languages such as French or Spanish, boundaries which are not present in infants' predispositions emerge from *couplings between predispositions* (Hoonhorst, Colin,

Deltenre, Radeau, & Serniclaes, 2006; see Figure 2c). These languages use a single distinction between negative VOT and moderately long positive VOT, and the boundary is located around 0 ms (Serniclaes, 1987).

*Insert Figure 2 here*

The combination between the two predispositions (voicing, e.g., negative VOT, and aspiration, e.g., positive VOT) is interactive in the sense that the perception of one feature depends on the perception of the other. Such “perceptual interdependencies” (Koffka, 1935) have been referred to with different terms in perceptual theories, among which “coupling” (Hochberg, 1981) is the most appropriate in the present context as it emphasizes the functional link between a new featural entity and its primitive components. Evidence for coupling between predispositions has been collected both for voicing (Hoonhorst et al., 2006) and for consonantal place of articulation (Serniclaes, Bogliotti, & Carré, 2003; Serniclaes & Geng, accepted).

#### Origin of allophonic perception: a coupling deficit

The existence of couplings between categorical predispositions for phonetic contrasts in the early stages of speech development suggests that the acquisition of language-specific distinctions does not only proceed by selection of pre-wired processes but that they also involve fairly complex combinations between predispositions. Previous data suggest that couplings between predispositions are deficient in children affected by dyslexia.

The evidence was based on increased within-category discrimination by dyslexic children vs. chronological age controls (Serniclaes et al., 2001) and, more specifically, on the

presence of within-category discrimination peaks in the discrimination functions of children with dyslexia. When discrimination of VOT contrasts by children affected by dyslexia were compared to those of reading age controls, both groups displayed a discrimination peak around the phonemic boundary but the dyslexic children also displayed a second discrimination peak at -30 ms VOT (Serniclaes et al., 2004). This latter peak is presumably allophonic in nature because it corresponds to one the two voicing boundaries in Thai (Lisker & Abramson, 1970), a language with three voicing categories (/d/, /t/ and /t<sup>h</sup>/, see Figure 2).

A child who perceives allophones rather than phonemes (e.g., /d/, /t/ and /t<sup>h</sup>/ in a language where only /d/ and /t<sup>h</sup>/ are phonemic) would have difficulties attributing the same written symbol (e.g., “t”) to sounds belonging to different categories in his or her oral repertoire (e.g., /t/ or /t<sup>h</sup>/). The mismatch between spoken categories and phonemes might lead to important problems for learning to read, even in fairly transparent orthographic systems. The establishment of grapheme-phoneme correspondences requires one-to-one, contextually invariant, relationships between phonemes and graphemes. Allophones are neither biunivocally related to graphemes nor contextually invariant; this renders the discovery of regularities between graphemes and speech sounds highly hazardous. Computer simulations support this hypothesis by showing that the suppression of “phonological attractions” between phonetic features, conceptually similar to the “phonological couplings” defined above, has significant negative effects on the reading performance of a connectionist network (Harm & Seidenberg, 1999). This supports the

contention that allophonic perception severely affects reading performances in human beings.

### THE CURRENT STUDY

The present study aims to assess the categorical perception deficit in dyslexics in comparison to chronological age and reading level controls by collecting both discrimination and labeling data on a VOT continuum.

The first objective was to reduplicate previous findings on categorical deficits in a single study and using the same method for testing both the discrimination and labeling deficits.

The second objective was to provide a further test of allophonic perception in children with dyslexia. We expected to find a higher allophonic discrimination peak in dyslexic children vs. controls and this peak should correspond to the natural negative VOT boundary (about -30 ms). The third objective of the present study was to assess categorical deficits by

comparing dyslexic children not only with chronological age controls but also with reading level controls. As previous studies do not unambiguously point to the presence of a

Categorical Perception deficit when comparing children with dyslexia to reading level

controls, we wanted to provide a further test of this hypothesis. The inclusion of young

normal reader children matched on reading level to children with dyslexia allows to assess

whether children with dyslexia would suffer from a developmental deviance or a

developmental delay in their categorical perception skill. The presence of a deficit would

mean that it is partly independent of reading experience or linguistic development. The

fourth objective was to assess the individual reliability of the categorical deficits and allophonic perception when compared to either chronological age or reading level controls.

## METHODOLOGY

### Participants

Twenty-one children in the 4th grade (10 years-old) and 10 younger children (mean: 7, 6 years-old) participated in our study. Children were selected using the following procedure: the parents of seventy-five 10 year old children received a questionnaire about participation in the present study, and we collected about 40 responses. From all these responses, we selected children (i) who were monolingual French speakers and had no auditory problems, (ii) who had average verbal and non-verbal IQs. Failure to fulfill either of these requirements was cause for exclusion from the study. According to a standardized reading test ("l'Alouette", Lefavrais, 1965, the children were classified as dyslexics or average readers (chronological age controls). They were 10 dyslexics (3 females, 7 males; the age range was from 9.04 to 10.03 year old) with a reading age at least 18 months below the expected reading age (see Footnote 2) and 11 chronological age controls (7 females, 4 males; the age range was from 9.04 to 10.03 year old) with a reading age above or equal to the expected lexical age.

The same procedure was used in order to select reading level controls: the parents of about 100 children received a questionnaire regarding participation in a longitudinal study (see Footnote 3) and we collected about 75 responses. Ten of these children (3 females, 7 males; the age range was from 6.09 to 8.01 year old) were matched with dyslexics

according to their reading scores: four were 1st graders, and six were 2nd graders. All reading level controls children had the reading level expected for their age: they presented a maximum of 1 month delay or 3 months advance in comparison to the expected lexical age.

Summary statistics of the main group characteristics are presented in Table 1. Non verbal IQ was assessed on Raven's Standard Progressive Matrices (SPM; Raven, 1976, and verbal IQ was assessed with the "Echelle de Vocabulaire en Images Peabody" (a French adaptation of the Peabody Picture Vocabulary Test Revised: Dunn, Thériault-Whalen, & Dunn, 1993) for the chronological age controls and dyslexics groups and with the "Test de Vocabulaire Actif et Passif" (Passive and Active Vocabulary Test: Deltour & Hupkens, 1980) for the reading level control group (see Footnote 4). In addition, we report the results obtained by each group in an assessment of their reading and reading related skills (based on the test battery "EVALEC", see Sprenger-Charolles, Colé, Béchennec, & Kipffer-Piquard, 2005. For reading related skills (phonemic awareness, and phonological short-term memory) there were only pseudowords in order to avoid biases due to differences in the children's vocabulary level. In addition, to avoid differences in experimenter's articulation, the items were recorded beforehand and the children heard them through headphones. For these two tests, as well as for the rapid naming test, practice items were first provided and no feedback was given during the test. For the phonemic awareness test, the children were required to delete the first 'sound' of 24 pseudowords, 12 with a consonant-vowel-consonant (CVC) structure, and then 12 with a consonant-consonant-vowel (CCV) structure. For the CVC test, the initial consonant was either a plosive or a

fricative (half of each). For the CCV test, a plosive (4 items) or a fricative (4 items) was followed by a liquid and a plosive was either followed (2 items) or preceded (2 items) by a fricative. For the phonological short-term memory test, the children were required to repeat three- to six-syllable pseudowords (6 items for each length, 3 with only CV syllables and 3 with a CVC syllable). The items were presented one at a time, in increasing order of length (the 6 three-syllable items first, followed by the four-, five-, and six-syllable items). The memory span measure was the number of syllables in the items of the last series for which at least four correct responses were given, and it could vary from 2 (when the child failed to correctly repeat at least 4 out of the 6 three-syllable items) to 6 (when the child was able to correctly repeat at least 4 out of the 6 six-syllable items). Naming speed was assessed by a serial naming task using color (six colors presented 8 times in a different order). Three items had a CVC structure: 'rouge' (red), 'jaune' (yellow), 'vert' (green), and three items had a CCV structure: 'bleu' (blue), 'blanc' (white), 'gris' (grey). The items were presented on a sheet of paper. For the reading skills, children were required to read aloud two lists of words and two lists of pseudowords presented on the screen of a computer. The words of the first list were orthographically regular and were matched to the first list of pseudowords according to their orthographical complexity. The words of the second list were either short or long orthographically irregular words matched to short and long pseudo-words according to their bigram frequency.

For all tasks, group differences were assessed by a repeated-measure ANOVA, and contrast analyses were done to test differences between dyslexics and either chronological age controls or reading level controls. The results are presented in Table 1.



There was a significant difference in chronological age between dyslexics and reading level controls but not between dyslexics and chronological age controls. Alternatively, there was a significant difference in lexical age between dyslexics and chronological age controls but not between dyslexics and reading level controls.

As regards IQ scores, there was no difference for Non-Verbal IQ between groups. Verbal IQ was higher in chronological age controls vs. dyslexics (see Footnote 4). However, the vocabulary level of all the children integrated in the study was within the normal range, be it assessed with EVIP (dyslexic children and chronological age controls) or with TVAP (reading level controls). For reading related skills, the dyslexics lagged behind both control groups for the two phonemic awareness tasks, although only the CVC scores were significantly different between the two latter groups. For phonological short-term memory, there was only a significant difference between the dyslexics and the chronological age controls. RAN scores were not significantly different between groups. In addition, the reading scores of the dyslexics lagged systematically behind those of the chronological age controls. The reading scores of the dyslexics also lagged behind those of the reading level controls but only for the reading of the short and long pseudowords, not for regular or irregular word reading.

*Insert Table 1 here*

## PROCEDURES

Stimuli. Categorical perception was evaluated on a /do-to/ VOT continuum, ranging from

-50 to +50 ms VOT, and developed with natural speech. We combined excerpts from 3 different stimuli: a French [do] with a negative VOT, an English [do] with a +19 ms VOT, and an English [to] with +70 ms VOT. This continuum was obtained by pasting a 50 ms negative VOT extracted from French [do], before the release of English [do]. Then we reduced the negative VOT in 10 ms increments. We then progressively replaced the post release segment of the English [do] with positive VOT excerpts take from the English [to] in five 10 ms increments. Stimuli were played at a comfortable level using Beyerdynamic DT290 headphones.

Speech perception tasks. For categorical perception tasks, participants were tested individually, seated comfortably in front of a laptop monitor. They were tested with the “Percept A” and “Percept AB” programs developed by Carré (see Footnote 5). They were first trained to relate stimuli and same-different discrimination responses to AX pairs (i.e. sequences of two stimuli, either identical or different) including the endpoints of the VOT continuum (-50 vs. +40 and -40 vs. +50 ms VOT, i.e. both pairs representing /do-to/). They were asked to indicate whether the pairs presented were identical or different by pressing the appropriate key on the computer. No feedback was provided. Children were allowed to continue the experiment if they reached the 75% correct discrimination threshold criterion. Then, AX discrimination responses were collected. Stimuli were presented in pairs including either two different stimuli or the same stimulus twice. Both “different” pairs (stimuli differing by 20 ms VOT, in two different orders, e.g., S1S3 and S3S1 which both represent /do-do/ syllables; or S6S8 and S8S6 which represent /do-to/ and /to-do/

syllables), and “same” pairs (e.g., S1S1 and S3S3, which both represent /do-do/ ; or S6S6 and S8S8, which both represent /to-to/) were presented in random order with equal frequency (4 presentations for each pair). As in the training trial, listeners were asked to indicate whether the pairs presented were identical or different. The inter-stimulus interval (ISI) was 100 ms and the inter-trial interval (ITI) was 1000 ms. Finally, children were tested on their identification skills. The 11 stimuli were presented 10 times in random order and the child had to identify them as /do/ or /to/ by pressing the appropriate key on a computer keyboard. The total test duration was of about 25 minutes (20 minutes for the identification task, 5 minutes for the discrimination task).

*Psychometric tests.* Group differences were assessed by a repeated-measure ANOVA, and a contrast analysis on group in this ANOVA permitted testing differences between dyslexics and either chronological age controls or reading level controls.

*Discrimination data processing.* Discrimination results were analyzed in terms of the percentage of “same – different” correct discrimination scores. For each stimuli pair, these scores were obtained by computing the mean percentage of “different” responses for pairs of acoustically different stimuli (e.g., 0 vs. +20 ms VOT pair, /do-to/), and “same” responses for pairs of identical stimuli (e.g., 0 vs. 0 ms VOT or +20 vs. +20 ms VOT pair, respectively /do-do/ and /to-to/).

Labeling data processing. Expected discrimination scores were calculated from the labeling data (Footnote 6). These scores are mathematically equivalent to the “same – different” observed discrimination scores and they were used for comparing the labeling and discrimination data on the same scale. The slopes of the labeling functions were also used for the sake of comparing the present data with the literature (see Introduction). The slope was measured separately for each subject using Logistic Regression with the Labeling Response as the dependent variable and VOT as independent variable. The Logistic function (McCullagh & Nelder, 1983) is fairly simple and it has been frequently used for fitting labeling curves in the studies on speech perception (e.g. Nearey, 1990, though other functions such as the Cumulative Normal (Finney, 1971) are also possible and the latter has also been used in speech perception studies. Equation 1 gives the most general form of the Logistic function.

Equation 1 :

$$P(\text{response}) = e^y / (e^y + 1)$$

where

$$y = \text{Logit}(P) = \log(P/(1-P)) = I + S \cdot \text{VOT}$$

where I stands for the intercept and S corresponds to the slope of the labeling function. The boundary, which corresponds to  $P=0.5$  or to  $\text{Logit}(P)=0$ , is obtained by taking  $-I/S$ .

Analysis strategy. Firstly, the difference in categorical perception between discrimination and labeling scores were tested in a VOT x Score Type (discrimination vs. labeling scores) x Group (chronological age controls vs. dyslexics vs. reading level controls) ANOVA, repeated over participants. Secondly, and as provided the VOT x Score x Group interaction was significant as expected, the differences between groups were tested separately on the discrimination scores and on the labeling scores with VOT x Group ANOVAs, repeated over participants. Between-group differences for the expected discrimination scores (labeling scores) were compared with those obtained for the slopes of the individual labeling functions. Differences between groups were tested separately for the dyslexics vs. chronological age controls and for the dyslexics vs. reading level controls. Differences in categorical perception and in allophonic perception were tested with VOT x Score Type x Group interaction contrasts. A Phonemic peak was computed as the difference between the across-category discrimination scores, i.e. those collected for the stimulus pairs straddling the phonemic boundary, and within-category discrimination scores, i.e. those collected for the stimulus pairs inside the two categories, either voiced or voiceless. An Allophonic peak was computed as the difference between the allophonic discrimination score, presumably corresponding to the stimulus pair straddling the -30 ms VOT value, and those collected for the other stimulus pairs inside the voiced category. As there were two contrasts per group comparison (dyslexics vs. chronological age controls and dyslexics vs. reading level controls), one for testing the Phonemic peak and the other for testing the Allophonic peak, P values for testing contrasts were Bonferroni corrected by

a factor two (i.e. the effective .05 P level was set at .025). All statistical analyses, at the exception of the Bonferroni corrections, were performed with the SPSS software.

## RESULTS

### Categorical perception: Difference between expected and observed discrimination scores

The labeling functions of the three groups of children are presented in Figure 3. As can be seen, the phoneme boundary (i.e. the 50% do-to response point) is located at about +15 ms VOT for each group. Observed discrimination scores and those expected from labeling are presented in Figure 4a, 4b and 4c for the dyslexics, chronological age controls and reading level controls respectively. For the controls, the observed discrimination scores were close to the predicted scores, thus showing a high level of categorical perception, whereas for children with dyslexia, observed discrimination scores did not match the expected scores. In addition, a second discrimination peak appeared at -20 ms VOT, which was absent for chronological age controls and reading level control group. This peak was located close to the expected VOT value (-30 ms, see Introduction), and will therefore be considered as “Allophonic”, as will be further commented in the Discussion.

*Insert Figures 3 and 4 here*

For the comparison between dyslexics vs. chronological age controls, a Score Type x VOT x Group ANOVA indicated that the Score Type x VOT x Group interaction was significant ( $F(8,152) = 2.85$ ,  $p < .05$ , Greenhouse-Geisser corrected;  $\eta^2 = .13$ ). For the comparison between dyslexics vs. reading level controls, a Score Type x VOT x Group ANOVA indicated that the Score Type x VOT x Group interaction was just significant ( $F(8,144) =$

2.65,  $p = .05$ , Greenhouse-Geisser corrected;  $\eta^2 = .13$ ). Accordingly, further analyses were conducted separately on the discrimination and labeling scores.

#### Categorical Perception: discrimination peak

For the controls (Figure 4b and 4c), stimulus pairs straddling the phonemic boundary (i.e. the pairs centered on +10 and +20 ms VOT) were strongly discriminated whereas discrimination scores for the pairs inside the same category were at chance level (50%). The observed Phonemic peak was fairly large, with a 17% and 14% difference between across and within category discrimination respectively for the chronological age controls and reading level controls (Figure 4b and 4c). Conversely, the observed Phonemic peak was quite low for the dyslexics (3% difference, Figure 4a) and a second discrimination peak, located at -20 ms VOT, was present for this group.

Differences in discrimination scores were tested separately for the dyslexics vs. chronological age controls and for the dyslexics vs. reading level controls in two VOT x Group ANOVAs. The VOT x Group interaction was significant for the dyslexics vs. chronological age controls ( $F(8,152) = 4.51$ ,  $p < .001$ ;  $\eta^2 = .19$ ) and marginally significant for the dyslexics vs. reading level controls ( $F(8,144) = 2.37$ ,  $p < .05$ ;  $\eta^2 = .12$ ). Examination of VOT x Group contrasts showed that the Phonemic peak difference between dyslexics and chronological age controls was significant ( $F(1,19) = 9.55$ ,  $p < .05$ ;  $\eta^2 = .33$ ), while the Phonemic peak difference between dyslexics and reading level controls was not significant ( $F(1,18) = 4.15$ ,  $p = .06$ ;  $\eta^2 = .19$ ). Allophonic peak differences were significant for both

dyslexics vs. chronological age controls and dyslexics vs. reading level controls comparisons ( $F(1,19)= 11.9, p<.01, \eta^2=.39$ ;  $19.6, p<.001, \eta^2=.52$ ; respectively).

### Categorical Labeling

Examination of the expected discrimination scores in Figure 4 indicates that fairly similar phonemic peaks were present for each group and that no secondary peak was visible for the dyslexics. Differences in labeling scores were tested separately for the dyslexics vs. chronological age controls and for the dyslexics vs. reading level controls in two VOT x Group ANOVAs. The VOT x Group interaction was not significant for both the dyslexics vs. chronological age controls and dyslexics vs. reading level controls comparisons (both  $F<1$ ). All the interaction contrasts of interest were non significant (all  $F <1$ ).

### Labeling scores vs. slopes

Labeling functions are presented in Figure 3. The slope of the function is steeper for the chronological age controls vs. reading level controls and dyslexics (in that order).

However, individual slopes were highly variable within groups and differences between groups were not significant when tested with ANOVA ( $F<1, \eta^2=.02$ ). Differences between groups remained non significant when tested with the non-parametric Mann-Whitney U test, so as to take into account the effect of possible outliers (for dyslexics vs. chronological age controls:  $Z=1.41, p=.16$ ; for dyslexics vs. reading level controls  $Z= 1.21, p=.23$ ). Although non significant, the differences between the slopes of the functions between groups might seem weird given the similarities in the mean expected



discrimination peaks (Figure 4). This was partly due to the reversals in the labeling curves of three among the ten dyslexic participants around the boundary region, which contribute negatively to the slope but positively to the between-category expected scores as the latter are ‘blind’ to the direction of the changes in labeling scores. Further, the floor and ceiling of the dyslexics’ labeling curve also contributed negatively to the slope but did not affect the within-category expected scores, as the latter only depend on differences between labeling scores.

As the groups also differed in the magnitude of the floor and ceiling values of the labeling curve, i.e. in the responses collected either below +10 ms VOT or above +20 ms VOT (see Figure 3), and given that differences in floor and ceiling values are not specifically captured by slope calculations, direct tests of the effect of group on the mean response scores in the VOT regions of interest were performed. Differences in floor values between groups were significant overall ( $F(2,168) = 11.8, p < .001, \eta^2 = .12$ ) and both the dyslexics vs. chronological age controls and dyslexics vs. reading level controls comparisons were significant ( $F(1,168) = 21.0, \eta^2 = 0.11$ ;  $13.8, \eta^2 = 0.08$ ; respectively, both  $p < .001$ ). Differences in ceiling values between groups were significant overall ( $F(2,84) = 3.60, p < .05, \eta^2 = .08$ ), the dyslexics vs. chronological age controls comparison was also significant ( $F(1,84) = 6.53, p < .05, \eta^2 = .07$ ) but the dyslexics vs. reading level controls comparison was not significant ( $F < 1, \eta^2 = .004$ ).

#### Individual reliability of categorical perception deficit

In order to assess the individual reliability of the Categorical Perception deficit, we ran a Statistical Discriminant Analysis on the Phonemic Peak (see Figure 5a for individual data). Results on individual reliability were strongly conclusive: 81% of the individuals were correctly classified when we compared dyslexics vs. chronological age controls, and 70% of the individuals were correctly classified when we compared dyslexics vs. reading level controls. The correct classification scores were obtained after cross validation ("drop-out" method: each individual score was classified according to the distributions of the other scores).

Finally, we also examined the reliability of the Allophonic Perception differences, using the Allophonic Peak as an index (see Figure 5b for individual data). The outcome of these analyses were also strongly conclusive, although individual reliability was now better when children affected by dyslexia were compared to reading level controls rather than chronological age controls: 71% of the individuals were correctly classified when we compared the dyslexics to the chronological age controls, and 75% of the individuals were correctly classified when we compared the dyslexics to the reading level controls.

*Insert Figure 5 here*

## DISCUSSION

### Categorical perception deficit

Our first aim in collecting the speech perception data presented in this study was to evaluate whether dyslexics presented a Categorical Perception deficit. We found such a deficit for the discrimination of speech sounds thereby confirming the results of several

previous studies (Brandt & Rosen, 1981; Godfrey et al., 1981; Werker & Tees, 1987; De Weirtdt, 1988; Reed, 1989; Serniclaes et al., 2001). While both the children affected by dyslexia and the control children exhibited a discrimination peak at the phonemic boundary, this peak was much smaller for the dyslexics. This confirms the Categorical Perception deficit in dyslexia. A related deficit in the labeling of speech sounds was also found. When the labeling data were tested on the same scale as the discrimination data – using “expected” discrimination scores from labeling – there were no significant differences in categorical perception between groups. Further, when using a classical index of categorical labeling, the slopes of the labeling functions, we also did not find significant differences between groups. Yet, the floor and ceiling of the identification curves were significantly related to the group: the floor portion of the curve (below +10 ms VOT, see Figure 3) was significantly higher for the dyslexics vs. both control groups and the ceiling portion of the curve (above +20 ms VOT) was significantly higher for dyslexics vs. chronological age controls.

### Allophonic Perception

The discrimination performances of the dyslexic children were not only characterized by a reduced phonemic boundary peak but also by a non-phonemic discrimination peak. This peak was located at -20 ms VOT, close to the -30 peak evidenced for another group of children affected by dyslexia in a previous study (Serniclaes et al., 2004). The difference in peak location between the two studies is probably due to stimulus factors, as stimulus details might induce slight differences in the location of the allophonic peak in much the

same way as they affect the location of the phonemic boundaries. While the phonemic boundary is located at 0 ms for neutral consonant and vowel articulation (Medina & Serniclaes, 2005), it is for instance located at some +10 ms VOT in the less neutral /do-to/ context used in the present experiment. Therefore, the -20 ms VOT peak evidenced in this experiment can be safely considered as “allophonic” in nature and lends further support to the hypothesis that dyslexics adopt a specific mode of speech perception, based on allophones rather than phonemes.

While an allophonic peak was clearly apparent in the discrimination responses of the dyslexic children, it was completely absent from the labeling data (see the expected discrimination scores in Figure 4). As explained above, the labeling deficit was totally absent in the present study. No wonder then if the allophonic peak was then also absent in the labeling data.

#### Comparisons between Dyslexics and Reading Level Controls

The categorical deficits evidenced in the present study were significant for both the comparison to chronological age controls and for the comparison to reading level controls. Contrary to previous studies (Boissel-Dombreval & Bouteilly, 2003; Foqué, 2004), children with dyslexia were shown to be weaker in Categorical Perception than younger children with the same reading level. We underline this result given that this study is the first one which reports a deficit in Categorical Perception in children with dyslexia in comparison to reading level controls. This suggests that the Categorical Perception deficit reflects a developmental deviance rather than a delay. Further, reading level controls did

not exhibit an Allophonic peak, thereby suggesting that Allophonic Perception is not simply due to a delay in reading acquisition.

### Individual Reliability

The present results showed that the reliability of the Categorical Perception deficit was fairly strong with fairly large correct classification scores (dyslexics vs. chronological age controls: 81%; dyslexics vs. reading level controls: 70%). Much the same result was found by Maassen et al. (2001) who studied the discrimination of voicing and place of articulation continua by 9 y.o. Dutch children. They found that discrimination scores allowed for correct classification of about 75% of the participants as dyslexics or normal readers (chronological age controls). The present study also shows that Allophonic Perception differences between dyslexics and controls are also strongly reliable (dyslexics vs. chronological age controls: 71%; dyslexics vs. reading level controls: 75%). All these results point to some 75% correct classification of dyslexics on the ground of categorical performances in speech perception, both vs. chronological age controls and vs. reading level controls. By comparison, the reliability of the classical phonological deficit is of about 80% (Ramus et al., 2003a) and the reliability of the auditory deficit is quite smaller (60% of correct classification). Thus, the reliability of the allophonic deficit is quite similar to that of the classical phonological deficit.

Although our study and that of Maassen et al. (2001) indicate that the Categorical Perception deficit is fairly reliable across individuals, the information about *individual* performance is too scarce in the literature to make strong conclusions. It is therefore

interesting to have a look at the reliability of the difference between *groups* in categorical perception across studies, i.e. the robustness of the Categorical Perception deficit.

Serniclaes, Bogliotti, Messaoud-Galusi, & Sprenger-Charolles (submitted) recently reviewed studies on the differences between dyslexic children and chronological age controls in the discrimination of speech continua. The difference in Categorical Perception was significant in about 75% of the tests found in 6 different studies.

#### Nature of the Categorical Perception deficit in children with dyslexia: an allophonic mode of perception

In summary, our results lend further support to the hypothesis that children affected by dyslexia have a categorical deficit in speech perception and are more sensitive to allophonic contrasts than are normal-reading children, either chronological age or reading level controls.

Languages display phonemic boundaries at different points on the voicing continuum. However, these different points are not determined at random. Taking foreign categorization patterns into account allows us to understand the precise location of the second peak for dyslexics. We know that Thai phonemic boundaries are located at approximately -30 ms and +30 ms VOT (Figure 2; Lisker & Abramson, 1970), and that prelinguistic children were able to discriminate 3 voicing categories separated by two VOT boundaries (Lasky et al., 1975; Streeter, 1976; Aslin et al., 1981). The within-category peak observed in dyslexics, which is located on the -20 ms VOT pair, corresponds approximately to one of two phonemic boundaries in languages with 3 VOT categories,

such as Thai. Of course, it is too early to parallel the possible categorization peak of Thai listeners with the one exhibited by our subjects without a direct comparison. But it is already clear that dyslexics exhibit a discrimination peak close to the -30 ms Thai phonemic boundary and this coincidence must be evoked. Furthermore, Burnham et al. (Burnham, Earnshaw, & Clark, 1991; Burnham, 2003) have also observed that children are sensitive to both native and non-native contrasts, and that discrimination between allophonic contrasts was stronger for children with less reading experience. Finally, Serniclaes, Ventura, Morais & Kolinsky (2005) observed that illiterates do *not* suffer from a categorical perception deficit, even though they showed less categorical *precision* than literates, which might be the consequence of written language deprivation or impairment. Illiterates are exposed to oral language and acquire normal categorical perception, but their lack of exposure to written language leads to a labeling deficit. This means that lack of exposure to written language cannot account for the categorical perception deficit and that the latter should be considered as a cause rather than a consequence of their reading deficiency. The lack of a Categorical Perception deficit in reading level controls observed in the present study supports this conclusion. Although RL controls display the same reading performances as dyslexics, the latter display weaker categorical perception performances.

#### Origins of allophonic perception: a coupling deficit

Some phonemic boundaries are not included in the infant's predispositions (i.e. the VOT boundary located at 0 ms in languages as French, Spanish and Dutch, (Serniclaes, 1987),

although they do appear fairly early in the course of language development (Eilers, Gavin, & Wilson, 1979; Hoonhorst et al., 2006). *Coupling* process suggests that a new boundary, irreducible to one of the two natural phonetic boundaries and which falls right between these two boundaries, has to be acquired. This process enabling such acquisition is fairly complex as it requires a specific combination between two natural distinctions. The combination between the two predispositions is interactive in the sense that the perception of one feature depends on the perception of other.

Results of the present study suggest a coupling deficit: children with dyslexia exhibit a second discrimination peak at about -20 ms VOT, a value close to one of the two natural VOT boundaries found in Thai listeners and prelinguistic children. The fact that children with dyslexia perceived the negative VOT boundary so easily compared to the phonemic boundary suggests that they have not developed couplings between the predispositions for perceiving voicing (e.g., negative VOT) and aspiration (e.g., positive VOT), which is evidence of a coupling deficit. So, allophonic perception should find its origin in this coupling deficit.

But if dyslexic children fail to couple phonetic features, they should also show an allophonic peak in the positive VOT region and at a different place on the continuum than the phoneme boundary control children. Instead, they display a positive VOT peak, although weaker, at the same spot on the continuum as the control children. This can be explained by the fact that the phonemic boundary in control children (around +15 ms for the present do/to continuum) is close to the allophonic positive VOT boundary (at some +20 or +30 ms). However, another possible explanation is that the coupling deficit is not



complete and that dyslexic children have partially begun to develop a phonemic VOT boundary. Future research using stimulus continua with a larger separation between allophonic and phonemic boundaries should allow to clarify this point. Finally, allophonic perception should correspond to a developmental deviance rather than a delay because dyslexics display an enhanced sensitivity to the negative VOT boundary, not only in comparison to chronological age controls, but also to reading level controls. This suggests that the allophonic sensitivity evidenced in dyslexic children is not a consequence of their lower reading level. In this way, the allophonic perception deficit is similar to other phonological deficits (pseudo-word reading: Rack et al., 1992; Van Ijzendoorn & Bus, 1994; Sprenger-Charolles et al., 2000; phonemic awareness: Manis et al., 1997)

#### Allophonic perception and its implication for reading and phonological abilities

While having only limited consequences for oral language, allophonic perception has strong repercussions on written language. Allophonic perception should not impede the categoricalness of perception, though Categorical Perception should be based on allophones rather than phonemes. While lexical access should not pose a problem for oral language processing (although it would be heavier in terms of information processing), the phonological coupling deficit has straightforward implications for written language acquisition. Allophonic representations are a significant handicap for the establishment of grapheme-phoneme correspondences because they disrupt one-to-one correspondences between graphemes and phonemes. A child who perceives allophones /d/, /p/ and /p<sup>h</sup>/ instead of phonemes /b/ and /p/ will have difficulty assigning the same graphic symbol “P”

to /p/ and /p<sup>h</sup>/. It should be stressed that, due to coarticulation, allophones are commonplace for the different features and different languages. Further, allophonic variation is not restricted to some rare occurrences of deviant productions because phoneme categories tend to be located midway between allophonic categories and phoneme distributions spread on both sides of allophonic boundaries.

To take the example of the voiceless allophones, the mean productive VOT of /p/ in French (about +20 ms: Serniclaes, 1987) is fairly close to the allophonic positive VOT boundary, and individual /p/ productions are distributed about equally above and below this boundary. This means massive difficulty with grapheme-phoneme correspondences for an allophonic perceiver. Moreover, this difficulty will emerge even in a fairly transparent orthographic system and will be amplified with higher degrees of orthographic opacity (for a review on the effect of orthographic opacity, see Paulesu, Demonet, Fazio, McCrory, Chanoine, Brunswick, Cappa, Cossu, Habib, Frith, & Frith, 2001; Ziegler & Goswami, 2005; Sprenger-Charolles et al., 2006).

The allophonic perception hypothesis might also explain other deficits observed in dyslexia. This mode of perception could have a strong impact on phonemic awareness, deficient in dyslexics, because it involves the manipulation of phonemes which do not exist in their phonological decoding process. It would also contribute to the phonological short term memory deficit which is also observed in dyslexics. The number of decoding units is indeed higher in a system that is based on allophones rather than phonemes, thus triggering a working memory overload. On the whole, allophonic perception offers a new conceptualization of dyslexia in terms of deficient phonological processing.

## CONCLUSION

The present study confirms the relationship between reading skills and speech perception. Using all available known criteria to assess categorical perception, we replicated the Categorical Perception deficit in children with dyslexia both for discrimination scores alone and for the difference between discrimination and labeling scores. There were also differences in categorical labeling between groups but these differences were not significant. Categorical perception differences were related to the better discrimination of an allophonic distinction, which lends further support to the hypothesis that dyslexics adopt a specific mode of speech perception, based on allophonic rather than phonemic categories. Categorical perception differences and the related differences in allophonic perception were found not only between dyslexics and chronological age controls, but also between dyslexics and reading level controls. Finally, examination of individual performances showed that both the deficit in categorical perception and the concomitant increase in allophonic sensitivity were fairly prevalent among children affected dyslexia.

## FOOTNOTES

1. VOT (Voice Onset Time): There are 3 possible voicing categories across languages, and these categories depend on VOT, which refers to the temporal relation between onset of “voice” (laryngeal vibrations) and release of the mouth closure Lisker & Abramson, 1964. The first category is characterized by the onset of voice before the closure release (negative VOT, e.g. /ba/); the second category is characterized by the quasi-synchrony of voice onset relative to the release (short positive VOT, e.g. /pa/), and the third category is characterized by a delay of voice onset relative to the release (long positive VOT, e.g. /p<sup>h</sup>a/). In languages where the 3 VOT categories are phonemic, such as Thai, listeners exhibit two boundaries for voicing perception : a negative VOT boundary and a positive VOT boundary (Abramson & Lisker, 1970).
2. It is to be noted that 8 children with poor reading skills were not included in the group of dyslexics because their reading level was between 17 and 6 months below the expected reading age.

It is to be added that the dyslexics included in the cohort were not supposed to suffer from spoken language impairment. As explained in the section “Participants”, the vocabulary level of all the children integrated in the study (included that of the dyslexics) was within the normal range. Moreover, according to several pre-tests (see Table 1), there were no significant difference in RAN between dyslexics and both control groups, and no significant differences in phonological STM between dyslexics and reading level controls. It is important to

note that the mean span of the dyslexics in the present study was fairly long (4 syllables) compared to the typical performances of SLI children (Newbury, Bishop, & Monaco, 2005; Graf Estes, Evans, & Else-Quest, 2007 ). Taken together, these results suggest that the dyslexics included in the present cohort were not suffering from spoken language impairment.

3. Reading level controls were taken from an independent study, in which our goal was to assess categorical perception skills in relation to reading acquisition. We followed these children for 3 years, from kindergarten until the 2nd grade. For our reading level controls, we chose ten children from this longitudinal study.
4. In studies with French-speaking children, we rely when possible (with 4 to 8-year-old children) on the TVAP (Deltour & Hupkens, 1980) to assess the level of vocabulary, because this test is well designed than the EVIP. Further, there were some words specific to Canadian French in the EVIP. However, the TVAP cannot be used with children older than 9 years old. Therefore, we reported the results of the specific test used with the three different groups (EVIP for the dyslexics and for the chronological age controls, TVAP for the reading level controls).
5. “Percept” Programs can be uploaded at <http://www.tsi.enst.fr/~carre/programme.html>
6. With two categories (A & B), a binary discrimination choice (AX discrimination experiment), S3, S4 as stimuli and with  $P(RA/S3)$  as the proportion A responses to S3, etc. Predicted discrimination score =  $\text{mean} \{ P(A/S3) * P(B/S4) + P(B/S3) * P(A/S4) \} / \{ (P(A/S3) * P(A/S3) + P(B/S3) * P(B/S3) + P(A/S4) * P(A/S4) + P(B/S4) * P(B/S4)) \}$

+  $P(B/S_4) * P(B/S_4) / 2$ }. This formula is similar to those used for comparing labeling and discrimination responses in the assessment of categorical perception (Pollack & Pisoni, 1971).

## ACKNOWLEDGEMENTS

This work was supported by the “Programme Interdisciplinaire du CNRS, CTI-53” to L. Sprenger-Charolles and W. Serniclaes.

## FIGURES AND TABLES

Figure 1. Criteria for assessing categorical perception as illustrated by data collected from French-speaking adults on a /do-to/ VOT continuum (Bogliotti, unpublished). Labeling responses (Figure 1a) indicate the location of the perceptual boundary (i.e. the 50% d-t response point, 15 ms VOT) and are also used for computing expected discrimination scores (Figure 1b, dotted line). Pairwise discrimination responses were collected with a 20 ms VOT difference between stimuli in a pair. The observed discrimination scores (Figure 1b, continuous line) are fairly close to the expected scores (Figure 1a, dotted line), indicating almost perfect categorical perception in the classical sense (Liberman et al., 1957). The magnitude of the Phonemic Peak, the difference between across vs. within category discrimination scores, is an index of categorical perception.



Figure 1.

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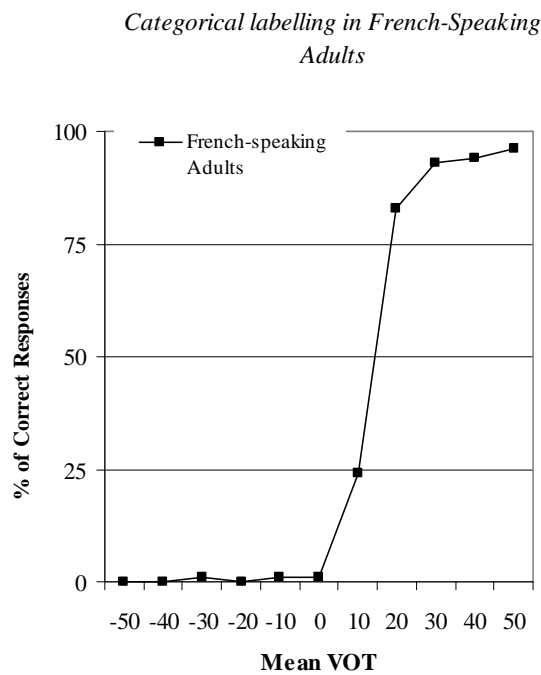


Figure 1a

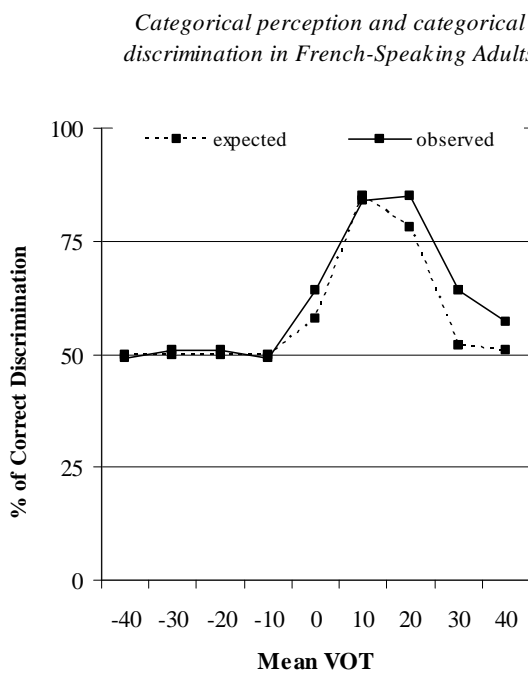


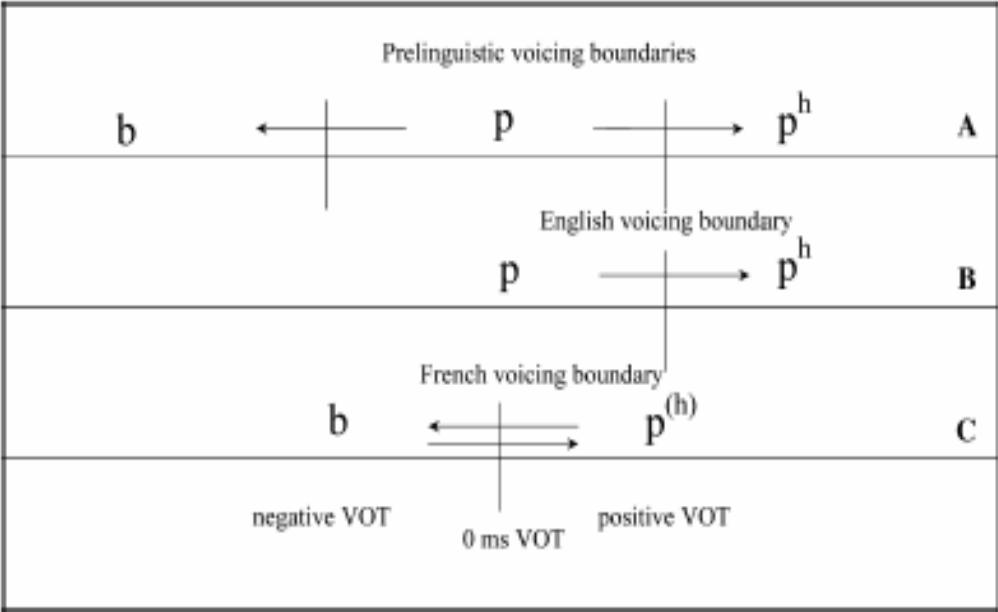
Figure 1b

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Figure 2. Perceptual boundaries between voicing categories: in infants (A), in English-speaking adults (B), and in French-speaking adults (C). Prelinguistic boundaries correspond to predispositions for the perception of all sound categories in the world's languages (indicated by arrows). In English, the natural boundary is activated and corresponds to a relevant phonological boundary between voiceless unaspirated stops and voiceless aspirated stops. In French, we observe a coupling between aspiration (positive VOT) and voicing (negative VOT) which generates a distinction between voiced stops and slightly aspirated voiceless stops (Serniclaes et al., 2004).

Figure 2.

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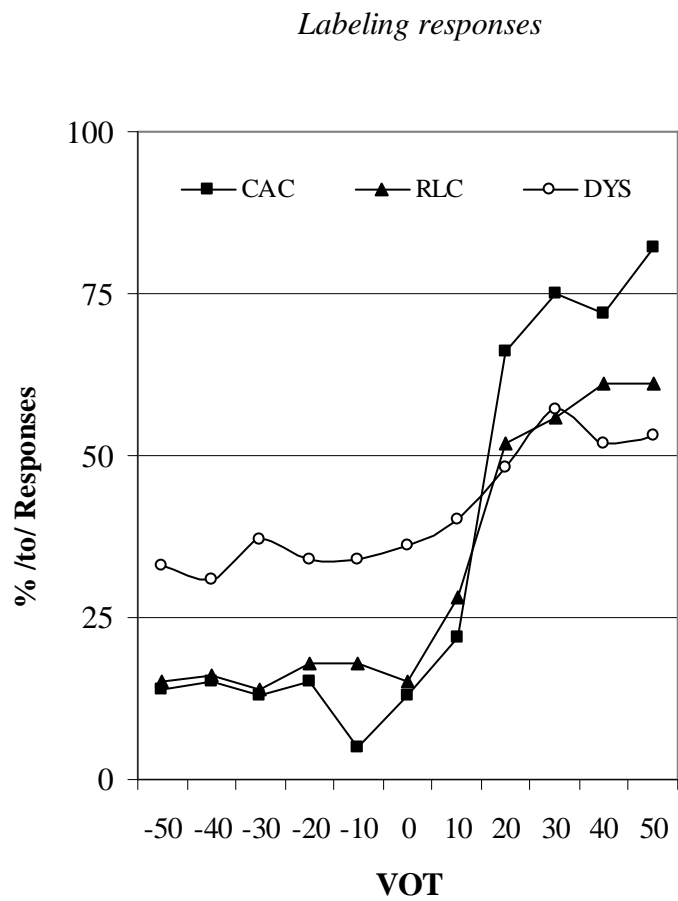


Bogliotti, C., Serniclaes, W., Messaoud-Galusi, S. & Sprenger-Charolles, L.

Figure 3. Labeling functions for dyslexics, chronological age controls and reading level controls (% of /to/ responses).

Figure 3.

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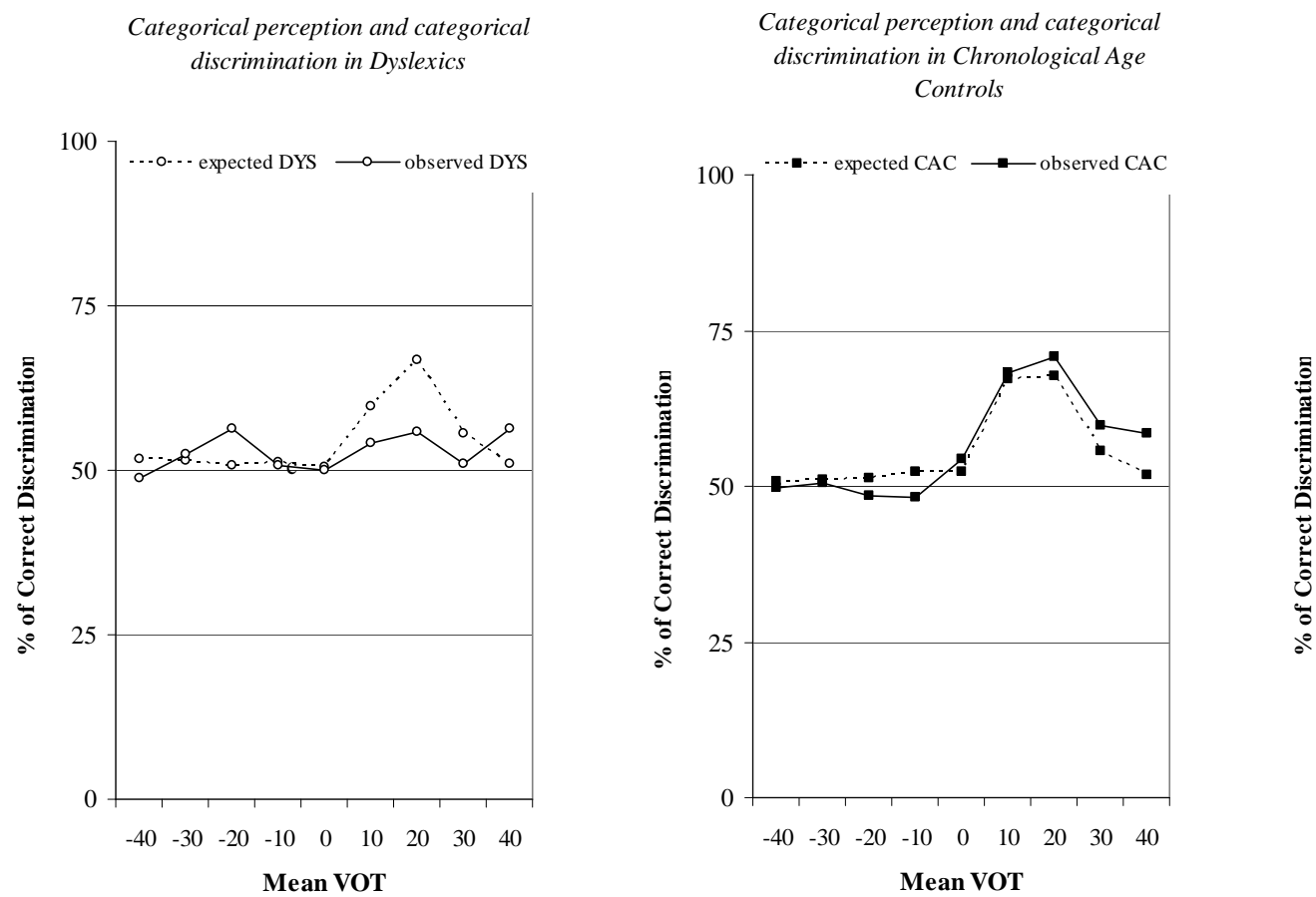


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Figure 4. Categorical perception in dyslexics (Figure 4a), chronological age controls (Figure 4b) and reading level controls (Figure 4c) on the /do-to/ voicing continuum (% of Correct Discrimination). Dotted lines represent expected scores and continuous lines represent observed scores.

Figure 4.

Top of the figure



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Figure 5. Individual *Phonemic* peaks values (i.e. difference between between-category discrimination score and the within-category discrimination score) for 3 groups of participants (Figure 5a). Dotted lines indicated classification limits obtained by a Statistical Discriminant Analysis. As the limit between the dyslexics and chronological age controls and the one between dyslexics and reading level controls were fairly close (Phonemic peaks of 10 and 9%, respectively) a single limit (at 9%) is reported on the graph. The distribution of dyslexic children and chronological age controls only slightly overlaps (81% correct classification). The overlap between the distribution of dyslexic children and reading level controls is larger (70% Correct Classification).

Individual *Allophonic* peaks values (i.e. difference between the -20 ms VOT discrimination score and the other negative and 0 VOT discrimination scores) for 3 groups of participants (Figure 5b). Dotted lines indicated classification limits obtained by a Statistical Discriminant Analysis. As the limit between the dyslexics and chronological age controls and the one between dyslexics and reading level controls were fairly close (Allophonic peaks of 2 and 1%, respectively) a single limit (at 1.5%) is reported on the graph. The distribution of dyslexic children and controls are fairly distinct (71% correct classification for the dyslexics vs. age controls; 75% correct classification for the dyslexics vs. reading level controls).



Figure 5.

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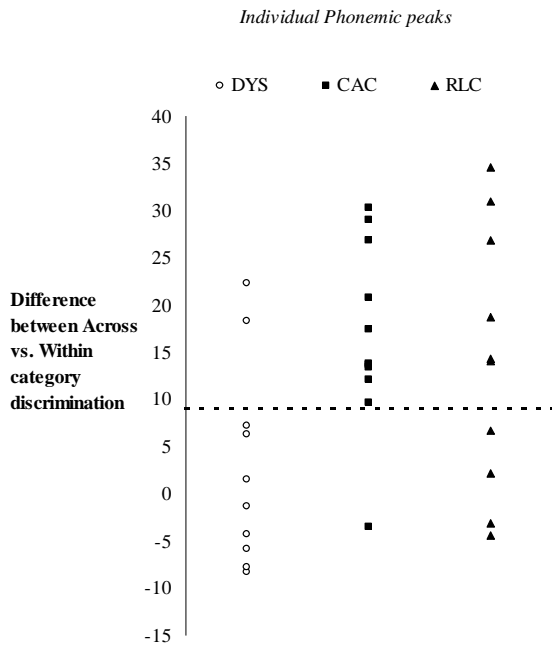


Figure 5a

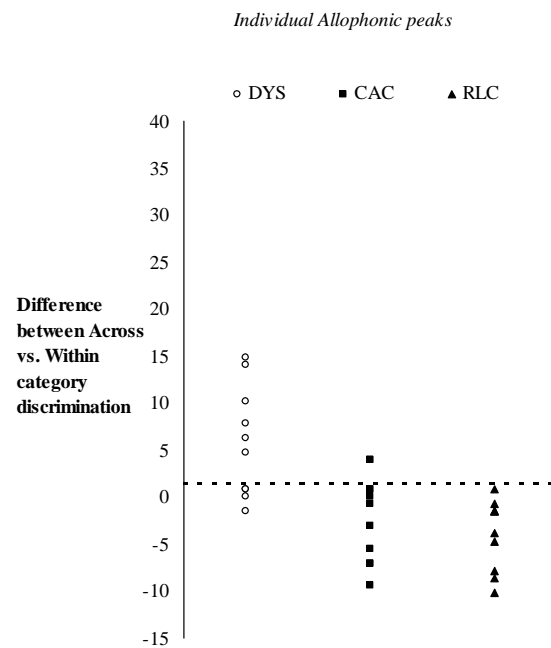


Figure 5b

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Regular Words (% Correct )	82	26	98 *	2	91	10
Regular Pseudowords (% Correct)	64	26	93 ***	5	73	18
Short Pseudowords (% Correct)	69	22	93 ***	8	88 *	16
Long Pseudowords (% Correct)	53	30	81 ***	11	73 †	24
Short Irregular Words (% Correct)	50	33	94 ***	8	52	20
Long Irregular Words (% Correct)	56	33	96 ***	7	59	26

Comparisons (dyslexics vs. chronological age controls and dyslexics vs. reading level controls) were done using contrast analysis in a repeated-measure ANOVA: \*\*\*  $p < .001$ ; \*\*  $p < .01$ ; \*  $p < .05$ ; †  $p < .06$

‡ Data from one (1) subject missing for Verbal IQ in the reading level control group.

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